Marine Magnetotellurics for base salt mapping: Gulf of Mexico Field-Test at the Gemini Structure

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Summary

The first successful marine Magnetotelluric survey in the Gulf of Mexico (GOM) has been conducted over the Gemini prospect. The survey, conducted in 1km of water, demonstrates that high quality electric and magnetic field measurements can be made on the seafloor in the GOM. The numerical forward and inverse modeling shows that this recorded seafloor data contains significant information regarding the shape of salt. In particular, smooth 2D inversions of the field data show the confined nature of the Gemini salt body and sharp boundary 2D inversions resolved the base of the salt to within a few percent of its depth down to a depth of 5km.

Introduction

Under the sponsorship from a consortium of major oil companies and the Department of Energy a collaborative effort between Scripps Institution of Oceanography (SIO), the University of California at Berkeley (UCB) and Lawrence Berkeley National Laboratory has developed equipment, algorithms, software and field techniques which together has made the application of Marine Magnetotellurics (MMT) to petroleum exploration possible. In June 1997 a demonstration survey was run over the Gemini prospect in the Gulf of Mexico. The Gemini salt structure is a complex 3-D salt body with a sub-salt oil and gas discovery by a partnership of Chevron and Texaco. This survey represents the first successful MMT survey conducted in the GOM for petroleum exploration.

SIO Seafloor MT System

The SIO seafloor electromagnetic recorder (Figure 1) is a state-of-the-art system based on two decades of development at SIO. It incorporates an acoustic navigation and release system, a modern digital data logger, custom electric field preamplifiers, low-noise electrodes designed for seafloor use, and commercial broad-band magnetic sensors in underwater pressure cases.

The seafloor instrument weighs approximately 150kg and with its electrode arms detached is easily transportable. The instrument can be deployed with or without the magnetic field sensors. This allows considerable flexibility in possible survey configurations. The instrument as shown in Figure 1 is configured as a complete MT site with orthogonal E and H measurement capability. The 5m electrode arms are detachable for shipping and onboard handling of the system. Constable et al. (in Press) gives a detailed description of the system.

Figure 1: SIO seafloor MT data logger going over the side of survey ship in the Mediterranean.

Data Acquisition and Processing

The interpreted top and base salt surfaces from a 3-D depth migrated volume were used to generate a 3-D finite difference numerical model (Mackie 1993) of the salt which incorporated the 1km of seawater over the prospect. The numerical MT data was used in an extensive experiment design phase. Inversion tests on the numerical data showed that data in the frequency band between 0.1 and 0.01 Hertz were critical to base salt resolution. In addition numerical tests showed that 2D inversion of the data should provide reasonable accuracy on the base salt.

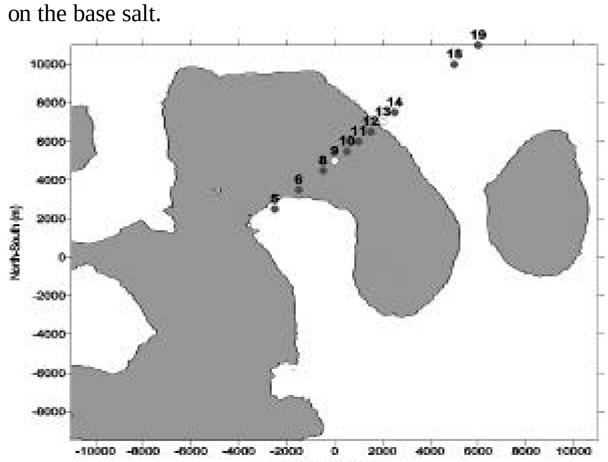

Figure 2: MMT Survey line. Dark shaded area – salt thickness > 500m. Seafloor site locations in black.

The survey design study guided the placement of the survey line that ran nearly N45E as shown in Figure 2. At the southwest end of the line the salt is very thin (<300m) and deep (5km). In the middle, beneath sites 10-12, the salt thickens to approximately 2 km and terminates just NE of site 12. Figure 2 shows the survey line in relation to salt greater than 500m thick.

The survey was conducted with two land sites used as reference sites for the remote-reference processing (Gamble et al. 1978). The remote sites were near Thibodoux, LA and Austin TX. Previous experiments over Gemini in 1996 had shown that instrument motion due to bottom currents could significantly degrade the magnetic field signals, so large 200kg anchors were employed in the 1997 survey resulting in greatly improved magnetic field data. Recording times were on the order of 24 hours at each site with variations due to the logistics of multiple deployments and recoveries.

The data were processed using the "robust" multi-station MT processing algorithms of Egbert (1997). This processing not only reduces outlier populations but also takes advantage of all simultaneous recordings to produce improved impedance estimates. Conventional industry processing was also done and compared to the robust results. The comparison showed that while the standard remote-reference processing recovered all major features of the data, the robust estimate contained less noise. Overall data quality was high and comparable to land data surveys. Figure 3 shows apparent resistivity and phase data from site 10, which is representative.

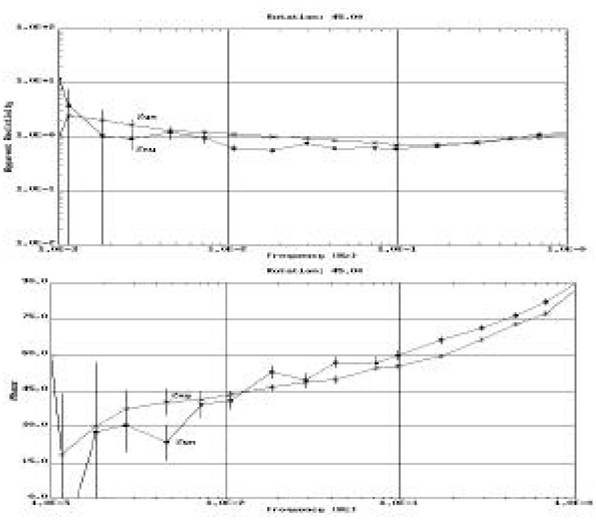

Figure 3: Apparent Resistivity (top panel) and Phase (bottom panel) at site 10. Data has been rotated so that Ex is in the line direction (NE). Zxy has been defined as TM mode.

All data were rotated so that the Zxy impedances had Ex orientated along the line direction. This rotation was consistent with the electrical impedance strike as shown by the polar diagrams. The Zxy impedances were defined as TM for 2D inversion of the data. Previous numerical modeling of salt structures, Hoversten et al. (1998) showed that 2D inversions of potential 3-D data are most accurate if only the TM mode is used. Therefore, all inversions of the Gemini data used TM mode only in the frequency range from 1 to 0.001 Hertz.

2D Inversions of Gemini Data

In order to test the relative performance of algorithms and also to provide enhanced confidence in the information content of the data, we used four different 2D MT inversion algorithms on the data. They were, 1) Smith & Booker (1988), 2) a non-linear conjugate gradient algorithm, Mackie (1997), 3) the Occam2D algorithm, de-Grood Hedlin & Constable (1990), and 4) the Sharp Boundary Inversion (SBI) algorithm, Smith et al. (1997).

The first three algorithms listed above find models that are smooth both vertically and horizontally. They were all started from a 0.7 ohm-m halfspace with no a priori information used as constraints. All three smooth inversions provided very consistent models in the following respect. First, all showed the presence of resistive (~ 1Ω-m) material just below the seafloor. Second, all had a sharp increase in resistivity that corresponded with the top salt as picked from the 3-D seismic. Third, all showed a zone just above salt that had lower resistivity than seawater. Fourth, all gave a similar picture of base salt down to a depth of approximately 5 km.

The fact that three different algorithms all gave very similar pictures and that they indicated the presence of a confined salt body in the correct location was reassuring. However, the smooth inversions provide a fuzzy base salt picture, which must be interpreted with the aid of inversion tests on numerical model data. In order to improve the resolution of the base salt we made use of some of the constraining features possible with the Occam2D algorithm and used the SBI algorithm in additional inversions.

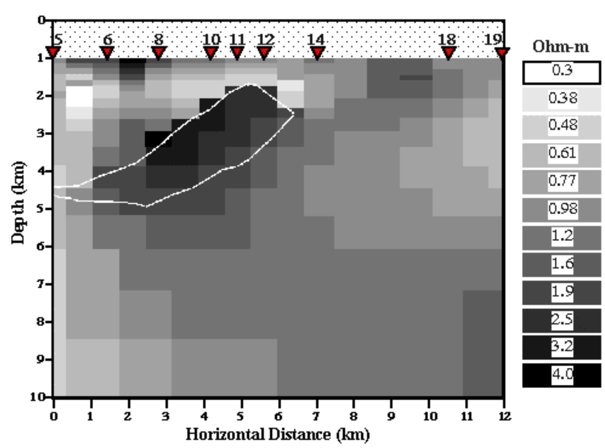

Figure 4: Occam2D TM mode inversion. Starting model was 0.5 Ω-m halfspace. White line shows salt outline as interpreted from 3-D prestack depth migrated data. No smoothing across blocks at top salt.

The Occam2D inversion shown in Figure 4 had the smoothing constraints eliminated across the location of the top salt. This allows the algorithm to place high resistivity salt next to low resistivity sediments at the top salt boundary. When smoothing is done across the top salt boundary the result is to push more resistive material to greater depths to accommodate the lack of higher resistive material at top salt, thus degrading the base salt image.

The 2D SBI inversion is parameterized to accommodate sharp contrasts in resistivity across boundaries and thus eliminate some of the ambiguity in interpreting smooth inverse models. Rather than parameterizing the model in terms of blocks whose resistivity is solved for, the SBI parameterizes the model in terms of vertical node locations of boundaries between layers and resistivities of the layers. The resistivities are defined laterally at the node locations and are constant vertically within each layer. The resistivities vary linearly between nodes in the horizontal direction within each layer. In order to stabilize the inversion a smoothing constraint is placed on the vertical node locations and on the horizontal variation of resistivity. At each iteration the layer resistivities are projected onto an underlying finite element mesh for the MT calculations.

Figure 5 shows the SBI model for the Gemini data.

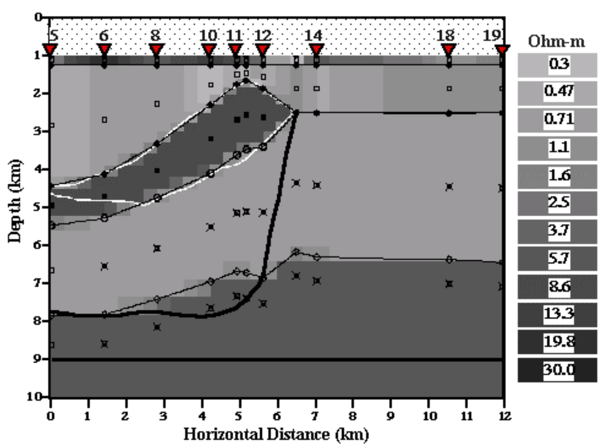

Figure 5: SBI inversion of Gemini data. Top of salt boundary location was fixed. Heavy Black lines indicate starting location of base salt and deep resistor. White line is salt outline from 3-D seismic.

Because the SBI is parameterized by layer boundaries a starting model with the appropriate number of layers is required. In this case the results from the smooth inversions were used as a guide in building the SBI starting model. In particular, a near-surface resistive layer was indicated. The presence of a deeper resistive layer was both indicated in the smooth inversions and in the apparent resistivity curves at lower frequencies. The starting location of the base salt was deep enough to encompass the high resistive zone shown on all the smooth inversions.

Nodes beneath the observation sites parameterized each layer. Additionally, a node was added between sites 11 and 12 to better describe the crest of the salt on the top boundary, and a node was added between sites 12 and 14 to describe the edge of the salt. Beyond site 12, where the seismic showed no salt the base salt layer was moved to coincide with the top salt and it location was fixed, effectively eliminating the salt layer to the northeast of site 12. The near-surface resistive layer was set at a constant thickness and only its lateral resistivity was allowed to vary. Because the top of salt was well determined by the seismic its location was fixed in the inversion.

One of the features of the SBI is the ability to fix, constrain or link parameters in the inversion. All these serve to reduce the possible variations in the model. For the Gemini data the sediment resistivities beneath the salt and the resistivities in the deepest (more resistive) layer were linked together so that these layers had constant resistivities laterally. In addition, the salt resistivity was fixed at 10 Ω-m. This is justified because the MT response saturates as the resistivity of a body becomes greater than 10 to 20 times that of the background. In the GOM bulk salt resistivities are greater than 20 times the background sediment resistivities. The MT response is totally governed by the distortion of electric currents in the sediments around the resistive salt. There is no contribution from induced currents within the salt itself. This greatly reduced the number of parameters needed in the inversion.

The SBI placed a base salt interface within a few percent of the 3-D seismic pick down to a depth of 5km. Below 5km where the salt is thinnest the SBI thinned the salt from the starting model until no more changes in the MT response occurred. The resulting salt model at the southeast end of the line beneath sites 5 and 6 represents the minimum thickness of salt, at this depth, which produces any MT response.

In addition to the base salt the inversions of the data indicated the presence of a deep resistive zone which could correspond to cretaceous sediments. The experiment was not designed to acquire the accurate low frequency data required to accurately position this deep resistor. Longer recording times would be required to improve data quality below 0.001 Hertz where information about the deeper structure is contained.

Conclusions

The 1997 Gulf of Mexico MMT survey represents the first successful survey of its kind. The survey was a success both in terms of high quality seafloor MT data acquisition and in terms of a successful interpretation of the resulting data. The inverse models, which fit the observed data, are of sufficient fidelity to answer significant exploration questions regarding the shape and location of base salt structures.

In addition, the models at Gemini offer the tantalizing potential of providing information of the deeper structure of the Gulf. The technology is moving into commercialization. The consortium is planning two additional test surveys in 1998; one in the North Sea to image the base of basalt structures and another in the Gulf of Mexico.

The consortium membership during the acquisition and processing of the data included AGIP, Anadarko Petroleum, BP, BHP, British Gas, Chevron, Texaco and Western Atlas.

Acknowledgements

The authors are grateful to the Marine MT consortium, in cooperation with the U.S. Department of Energy, Office of Energy Research, Office of Laboratory Technology Research under Contract DE-AC03-76SF0098, for their support of this research.

The authors would also like to thank Mary Ann Mulrey and Ransom Reddig of AOA Geophysics and Clark Scott and Diane Gievers of Engineering Geoscience UC Berkeley for their work in data acquisition and processing.

Electromagnetic Instruments Inc. supplied MT acquisition systems for the survey.

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